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Effect of Model Structure on the Uncertainty of Results From Watershed Scale Water Quality Models

G. P. Fernandez, Research, Associate

Department of Biological and Agricultural Engineering, P.O. Box 7625, North Carolina State University, Raleigh, NC, 27695, gfernand@eos.ncsu.edu

G. M. Chescheir, Research Assistant Professor

Department of Biological and Agricultural Engineering, P.O. Box 7625, North Carolina State University, Raleigh, NC, 27695, cheschei@eos.ncsu.edu

D. M. Amatya, Research Assistant Professor

Department of Biological and Agricultural Engineering, P.O. Box 7625, North Carolina State University, Raleigh, NC, 27695, dmamatya@eos.ncsu.edu

R. W. Skaggs, William Neal Reynolds and Distinguished University Professor

Department of Biological and Agricultural Engineering, P.O. Box 7625, North Carolina State University, Raleigh, NC, 27695, skaggs@eos.ncsu.edu

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Abstract. Two lumped parameter watershed scale hydrology and water quality models (WATGIS and QUALGIS) which describe the nitrogen loadings at the outlet of coastal plain watersheds were examined with respect to their accuracy and uncertainty of model results. Latin Hypercube Sampling (LHS) was applied to **determine** the impact of uncertainty in estimating field exports and decay coefficients on the uncertainty of the simulated nitrogen loads at the outlet of a 2950 ha coastal plain watershed in eastern North Carolina. Analysis showed that QUALGIS can better predict the outflows and nitrogen loads at the outlet of the watershed as compared to WATGIS. For both models, the uncertainty in quantifying the field exports has greater impact on the uncertainty of outlet loads than does the uncertainty associated with decay coefficient. The uncertainty of predicted outputs from both model are similar.

Keywords. Hydrology, Water Quality, DRAINMOD, Uncertainty Analysis

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EFFECT OF MODEL STRUCTURE ON THE UNCERTAINTY OF RESULTS FROM WATERSHED SCALE WATER QUALITY MODELS

G.P. **Fernandez**, **G.M.** Chescheir, D.M. **Amatya** and R.W. **Skaggs**,¹

Abstract

Two lumped parameter watershed scale hydrology and water. quality models (WATGIS and QUALGIS) that describe the nitrogen loadings at the outlet of coastal plain watersheds were examined with respect to their accuracy and uncertainty of model results. Latin Hypercube Sampling (LHS) was applied to determine the impact of uncertainty in estimating field exports and decay coefficients on the uncertainty of the simulated nitrogen loads at the outlet of a 2950 ha coastal plain watershed in eastern North Carolina. Analysis showed that QUALGIS can better predict the outflows and nitrogen loads at the outlet of the watershed as compared to WATGIS. For both models, the uncertainty in quantifying the field exports has greater impact on the uncertainty of outlet loads than does the uncertainty associated with decay coefficient. The uncertainty of predicted outputs from both model are similar.

¹ Research Associate, Research Asst Professor and Research Asst Professor, and WNR and Distinguish University Professor Biological & Agricultural Engineering Department, North Carolina State University, Raleigh, NC 27695.

Introduction

Models of varying complexities have been developed at the North Carolina State University for characterizing the effects of land and water management practices on the hydrology and water quality of watersheds with poorly drained soils. These models are based on a mechanistic field hydrology model, DRAINMOD (Skaggs, 1978), coupled with different approaches to route water and nitrogen loads from the field edge to the watershed outlet. The models range from the simplified, lumped parameter approaches that use export coefficients and delivery ratio concepts (Amatya et al., 2001, 2002; Fernandez et al., 1999, 2000, 2002) to the more mechanistic and process-based models (Konyha and Skaggs, 1992; Amatya et al., 1998, 1999; Fernandez et al., 1997, 2000, 2001). The simplest model, WATGIS, (Fernandez et al., 1999, 2002) uses export concentrations and delivery ratios to calculate the loadings at the outlet of the watershed. Another model, QUALGIS, (Fernandez et al., 2000) uses a simplified transport model based on approximate solution of the diffusion equation. This model uses a spatially distributed response function to route water and loads from the field edge of contributing areas to the watershed outlet. On the other end of the spectrum are the more mechanistic models, DRAINMOD-DUFLOW (Fernandez et al., 1997) and WATMOD (Fernandez et al., 2001). These models use numerical solution to the Saint Venant equation combined with an ADR equation for pollutant transport and a flexible in-stream water quality model.

When coupled with uncertainty analysis component, these models are potentially useful tools for planning and decision making. Determination of uncertainties in model outputs is of great importance considering that there are inherent limitations of the models in describing the physical processes and the underlying uncertainties in model inputs and parameterization. The model parameters, boundary conditions, forcing functions, input variables, and other factors that are used in model simulations are generally not known with certainty., (Melching et al., 2001). In general, the uncertainty in model predictions is a function of uncertainties in model parameters, input data and model structure. It is often believed that a more comprehensive model is better able to simulate reality since the more complex the model, the more processes are described (Perk, 1997). However, in more comprehensive models, there will be more process parameters that need to be identified and quantified with certainty.

First Order Analysis (FOA), Monte Carlo Simulation (MCS) and Latin Hypercube Sampling (LHS) are uncertainty analysis methods developed and widely used in water resources engineering. Uncertainty methods allow consideration of the combined effects of parameter sensitivity and uncertainty in model predictions. The FOA is based on linearizing the functional relationship between a dependent random variable and a set of independent random variables by Taylor series expansion (Tung and Yen, 1972; Dettinger and Wilson 1981; Yen et al., 1986; Chaubey et al., 1999). In MCS, stochastic inputs are generated from their probability density function and are then entered into

experimental or analytical models of the underlying physical processes involved in generating stochastic outputs (e.g. Salas, 1993; Melching et al., 1996). Latin Hypercube Sampling is an alternative method that generates random samples of the parameter in a stratified manner (McKay 1988, Salas et al., 1999).

This paper describes a methodology and application of uncertainty analysis on two DRAINMOD based watershed scale hydrology and water quality models. We extend the previous studies of Fernandez et al., (2000, 2002) to compare the impacts of model structure on the uncertainty of outputs from two lumped parameter water quality models, WATGIS and QUALGIS. The paper addresses the two aspect of adequacy of the models, namely accuracy and uncertainty in quantifying loads from poorly drained coastal watersheds. Analyses were conducted for a 2950 ha managed forested watershed in the lower coastal plain of eastern North Carolina.

Watershed Scale Models

WATGIS

WATGIS is a Geographic Information System (GIS)-based, lumped parameter water quality model that was developed to estimate the spatial and temporal nitrogen loading patterns for lower coastal plain watersheds in eastern North Carolina (Fernandez et al., 1999, 2002). The model uses a spatially distributed delivery ratio (DR) parameter to account for nitrogen retention or loss along a drainage network. Delivery ratios are calculated from time of travel and an exponential decay model for in-stream dynamics. Travel times from any point in the drainage network to the watershed outlet are obtained from a regression model which expresses the travel times as a nonlinear function of upstream contributing area, length of flow path and mean field drainage outflow. Nitrogen load from contributing areas in the watershed delivered to the main watershed outlet is obtained as the product of field export with the corresponding delivery ratio. The total watershed load at the outlet is the combined loading of the individual fields. Inputs to the model include exports from source areas that are measured or modeled, decay coefficient and the field parameters used in DRAINMOD.

QUALGIS

QUALGIS (Fernandez et al., 2000) is a linkage of the field hydrology model DRAINMOD and a generalized spatially distributed canal routing model using a response function (Olivera, 1996; Olivera and Maidment, 1999). Field hydrology is simulated with DRAINMOD and the drainage network routing is done through an impulse response function using a first passage time distribution for the time of travel in the flow path. This model uses a generalized approach to flow routing which considers spatially distributed inputs and parameters where drainage from contributing areas (non-overlapping) are considered separately instead of spatially averaged. A two parameter routing

response function model (derived from first passage time distribution) was developed for each contributing area in which parameters are related to flow time (advective velocity) and shear effects (dispersion) along the flow path.

In this model, DRAINMOD is used to simulate the water losses from contributing areas (either under controlled or conventional drainage). The water losses are then routed to the field outlets using an instantaneous unit hydrograph and eventually routed to the watershed outlet using the response function. The model requires stream velocities along the flow path from contributing area to the watershed outlet as inputs. These could be determined from simulations using mechanistic models (Fernandez. et al., 1997, 2001) or could be determined from flow records. For water quality, an exponential decay model is used to characterize the attenuation of a water quality parameter as it travels along the flow path. Similar to WATGIS, field exports used in the model may be either measured or modeled.

Methodology

Site Description

The study watershed is a 2950 ha drained managed forest watershed (S4 in Fig. 1) located in Weyerhaeuser Company's Parker Tract in Washington county in eastern North Carolina. The soils of the watershed consist of both organic (primarily Belhaven and Pungo series) and mineral soils (poorly drained Portsmouth and Cape Fear series). The drainage system consists of field ditches which are 100 m apart leading to collector canals at about 800 m intervals which outlet to main canals about 1600 m (one-mile) apart. Surface cover of the watershed is characterized by second growth mixed hardwood and pine forest and loblolly pine plantation of various ages and stages (Weyerhaeuser, 1997).

Flow and drainage water for water quality are sampled from several gauging and sampling stations within the watershed (Fig. 1). Gauging stations are located at four field drainage outlets (F3, F5, F6 and F7), three on the main drainage canals (S1, S2, and S3) and one at the outlet of watershed (S4). Instrumentation at the automatic stations includes sharp crested 120° V-notch weirs, water level recorders, automatic samplers and microprocessors to store data and control the samplers. Chescheir et al., (1998) presented a detailed description of the network of monitoring stations for both flow and water quality sampling for this sub-watershed.

Simulation

The watershed was divided into 27 fields with the drainage network discretized into 46 canal segments. The fields were assumed

homogenous with respect to soils, surface cover and water management practices. Field areas and stream lengths were obtained from field surveys. In the absence of measured soil water characteristics for all the fields, properties of the dominant soil series in each field were obtained from published values as reported in Skaggs and Nassadzadeh-Tabrizi (1986) and Amatya et al., (1998).

Water quality data (nitrate-nitrogen) collected from 1996-1999 composite and grab samples from five experimental fields in the S4 watershed were used to generate the concentrations and export coefficients for the individual fields. Average monthly flow weighted concentrations were obtained and distributed to the individual fields based on similarities in soil type, water management practice, stand age and type of surface cover. The flow weighted concentrations from the experimental fields range from 0.2 to 7.6 mg/l. These values are unusually high for forested lands in eastern North Carolina. For natural and forested lands in eastern North Carolina, Chescheir et al. (2002) reported mean nitrate concentrations in drainage waters of less than 0.6 mg/l.

Uncertainty Analysis

Latin Hypercube Sampling (LHS) (McKay 1988) is a stratified sampling approach that allows efficient estimation of the statistics of output. In LHS, the probability distribution of each basic variable is subdivided into N ranges each with a probability of occurrence equal to $1/N$. Random values of the basic variables are generated such that each range is sampled only once. Output statistics and distributions of the output variables are approximated from the sample of N output values. Using this approach in previous studies, Fernandez et al., (2000, 2001) showed that for drainage routing and water quality modeling using QUALGIS and WATGIS, uncertainties in the decay coefficient and field export concentrations have greater impact on the the uncertainty in simulated outlet loads. In this paper, we follow the procedure of performing uncertainty analysis using LHS as described by Salas et al., (1999):

1. For an input x , obtain n uniform random numbers, U_1, U_2, \dots, U_n in the range of 0-1.
2. Define $P_i = (1/n) [U_i + (i-1)]$ ($i=1 \dots n$). Then the P_i falls exactly within each of the n intervals, $(0, 1/n), (1/n, 2/n) \dots ((n-1)/n, 1)$.
3. From the cumulative distribution function $F(x)$ of the input x , determine the values $x_i = F^{-1}(P_i)$ ($i=1, \dots, n$). Then $x = [x_1, x_2, \dots, x_n]$ is the sample vector of the stochastic input x .
4. Perform random permutation of the set (x_1, x_2, \dots, x_n) obtained in step 3.
5. Repeat steps 1-4 for all inputs.

This procedure assumes that all inputs are independent. However, in the case of correlated inputs, the joint distributions of the inputs have to be considered.

LHS was used to generate 300 random samples of the field exports and decay coefficients used in both models. The objective function is the cumulative nitrate load at the watershed outlet. Mean, variances, coefficient of variations and the probability density functions for the model parameters were obtained from measured values at the watershed (export coefficients) or estimated from literature (decay coefficient). Having no evidence to the contrary, it was assumed that the parameters have negligible correlation. Results of the uncertainty analysis were summarized in the form of cumulative distributions of the objective function with corresponding confidence limits. Uncertainties in predicted outlet loads from both models were compared.

Results and Discussion

The main objective of the study was to determine capability of the models to accurately simulate the nitrate-nitrogen loads from coastal plain watersheds. In addition to this, we compare the uncertainty of the predictions of the two models. Flow and nitrate-nitrogen concentration data from 1996 were used for calibration and data from 1997-1999 were used for the evaluation of the models.

Simulations

DRAINMOD predictions of the temporal trend and magnitude of monthly flows at S4 agrees closely with the observed flows (Figure 2 & 3). Over the 10-month calibration period, the predicted monthly flows from both models were highly correlated with the measured flows ($p = 0.90$ for both models). The Nash-Sutcliffe R^2 values are 0.66 and 0.71 for WATGIS and QUALGIS, respectively. Measured and predicted monthly flow data for the evaluation period yielded Nash-Sutcliffe coefficients of 0.94 (WATGIS) and 0.92 (QUALGIS) and correlation coefficient of 0.97 for both models. WATGIS under-predicted the outflow by 2% while QUALGIS by 1%. Differences between observed and predicted values for both models were not statistically significant at 5% level. Overall, for the 46 months of data, the percentage error of prediction of QUALGIS is lower than that of WATGIS (0.7% compared to 1.4%).

To a large extent, the over-prediction of the models in 1996 was due to the over-prediction of peak flows during the occurrence of tropical storms (late summer to fall). However, the observed flows were probably underestimated because the weir at the outlet was submerged. In WATGIS, the field outflows were not routed to the outlet (sum of outflows for all fields is the total outlet flow), hence, errors in flow prediction can be also attributed to neglecting the effects of routing the flow from the source areas to the outlet. Daily peak flows

predicted by QUALGIS are lower than that of WATGIS. QUALGIS uses a simplified routing method, although effects of in-stream structures are not considered. This under-prediction during the evaluation period can be attributed to errors in estimating watershed rainfall and/or PET during the late winter and spring.

The trend in the prediction of nitrate-nitrogen loads at the watershed outlet was similar to the results for outflows (Figures 4 & 5). Over-prediction of outflows in 1996 resulted in 1% over-prediction of nitrate load by WATGIS and 1% under-prediction by QUALGIS. Comparison of the monthly measured and predicted loads yielded Nash-Sutcliffe coefficients of 0.6 (WATGIS) and 0.65 (QUALGIS). The correlation coefficient is 0.80 for both models. In contrast to the flow predictions, nitrate-nitrogen was over-predicted during the evaluation period. WATGIS over-predicted the outlet load by as much as 6% while over-prediction of QUALGIS was only 2%. The Nash-Sutcliffe and correlation coefficients were 0.84 and 0.92 for both models, respectively. Overall, for the 46 months data, the percentage prediction error for the watershed load is 4% for WATGIS and 1% for QUALGIS. The results show that the QUALGIS model is slightly better in predicting the flow and nitrate-nitrogen loads at the watershed outlet. The errors in prediction of the loads cannot be attributed solely to the errors in flow predictions. Errors in estimating export concentrations at the field edge would have contributed to the errors in the load predictions. Measured concentrations from five fields were extrapolated to the remaining twenty-two fields based on soils and surface cover.

Uncertainty Analysis

Results of the uncertainty analysis indicated that the variance of the outlet load due to the uncertainties in export concentrations were slightly higher for the WATGIS model as compared to the QUALGIS model (Table 1). The confidence limits (at 90%) of the mean annual outlet load due to the variability in field exports are almost the same for both models (0.25 for WATGIS and 0.23 for QUALGIS). The corresponding intervals are also similar. The uncertainty in predicting the watershed load using WATGIS produces a slightly wider confidence interval than that of QUALGIS. A different result was obtained with the uncertainty due to the decay coefficient. The variance of the outlet load due to the uncertainty in the decay coefficient was higher for the QUALGIS model (0.27) as compared to the QUALGIS model (0.13). This translates to a confidence limit that is larger for the QUALGIS model than that of the WATGIS model (Table 1). The results show that the uncertainty of the outputs of the two models is more dependent on the uncertainty of the field exports.

Although the uncertainty analyses indicated that the models are less sensitive to the choice of the decay coefficient, this parameter is probably the most uncertain and can be hard to estimate. As used in the model, this parameter integrates the rates of the processes that describe the cycling of the nutrient within the stream network.

Table 1. Statistics of simulated nitrate-nitrogen load at S4 for 1996 as function of uncertainty in export concentrations (EXPC) and decay coefficient (KC) (n=300)

		Mean (kg/ha)	Variance	CV (%)	90% CL	std. Error
WATGIS	EXPC	12.6	6.8	21	0.25	0.15
QUALGIS	EXPC	12.1	5.7	20	0.23	0.14
WATGIS	KC	12.6	0.1	3	0.03	0.02
QUALGIS	KC	12.2	0.3	4	0.05	0.03

The cumulative distribution of outlet loads is shown in Figures 6-7. The curves show the expected magnitude of the outlet load at a given probability level. For example, the probability that annual nitrate-nitrogen load at the outlet is greater than 9.4 kg/ha is 90% (Figure 6) considering the uncertainty in the field exports (WATGIS model). The curves also show the confidence limits on the mean response. The 90% confidence limits on the predicted mean outlet loads are relatively narrow indicating small standard errors in the predictions (≤ 0.3 kg/ha). Uncertainty in the export concentrations has significant impact on the uncertainty in the cumulative outlet load (Table 1). For WATGIS, the variability in outlet load is 21% and 3%, for the export concentration and decay coefficient, respectively. On the other hand, for QUALGIS, the variability in outlet load is 20% and 4%, for the export concentration and decay coefficient, respectively.

Summary and Conclusion

Two watershed scale lumped parameter hydrology and water quality models were evaluated to determine their accuracy in estimating watershed nitrate loads. In addition, the impacts of uncertainty in field exports and decay coefficient on the predicted watershed load were investigated. The model which links DRAINMOD field hydrology and a spatially distributed routing model using a response function (QUALGIS) was shown to reasonably predict the outflows and outlet loads from a lower coastal plain watershed. Predictions of QUALGIS model for both flow and nitrate load are more accurate as compared to the predictions using the WATGIS model.

The analysis showed that uncertainty in determining field exports have greater impact on the uncertainty in the prediction of nitrate loads at the outlet compared to the decay coefficient. Variability in predicted cumulative outlet loads as a result of uncertainty in this parameter was 21% and 20% for WATGIS and QUALGIS, respectively. These values are much greater than the variability in outlet loads due to

the uncertainty in the decay coefficients (3% and 4%). Accurate estimation of the field exports could greatly reduce the uncertainty in nutrient load predictions at the watershed outlet.

With regards to the models, QUALGIS appears to be a better model than WATGIS. QUALGIS is more accurate than WATGIS in predicting outflows and nitrate loads, although the uncertainty of the predictions are similar to WATGIS. QUALGIS uses a simplified routing model, hence, travel times along the drainage network are better estimated than the simple regression use in WATGIS.

Acknowledgement

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North Carolina

Lower Coastal Plain

Upper Coastal Plain

To Albemarle Sound

1 km

N

Legend:

- ☐ Agriculture
- ☒ Managed Forest
- ☒ Natural Forest
- ☒ S4 Watershed

Station Types:

- T4** Automatic Stations
- AG1** Manual stations
- R1** Rainfall Stations
- SS1** Stream Sections

The map shows the S4 Watershed in North Carolina, divided into sub-watersheds R1 through R8. The watershed is surrounded by the Upper Coastal Plain and Lower Coastal Plain. The map includes a legend for land use (Agriculture, Managed Forest, Natural Forest, S4 Watershed) and station types (Automatic Stations, Manual stations, Rainfall Stations, Stream Sections). The map is oriented with North at the top and includes a scale bar for 1 km. The watershed is located near the Atlantic Ocean and the Albemarle Sound.

11

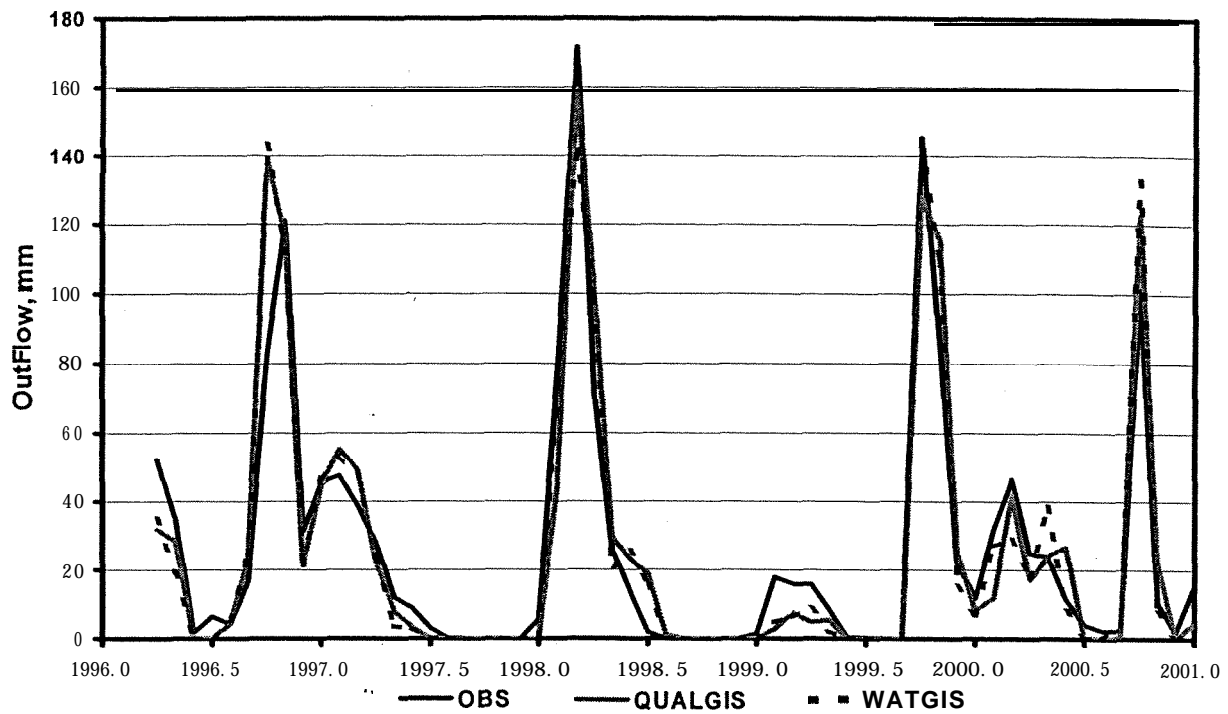


Figure 2. Predicted and observed outflows at S4 (1996-2000).

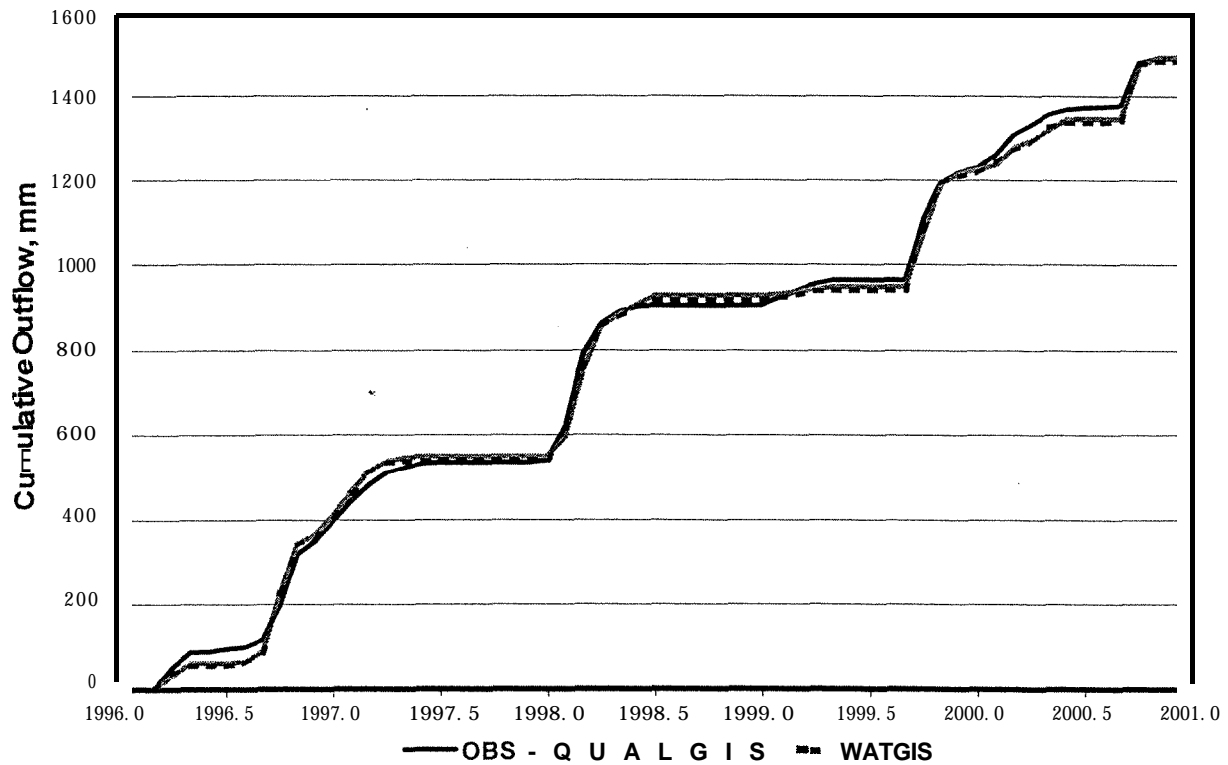


Figure 3. Predicted and observed cumulative outflows at S4 (1996-2000).

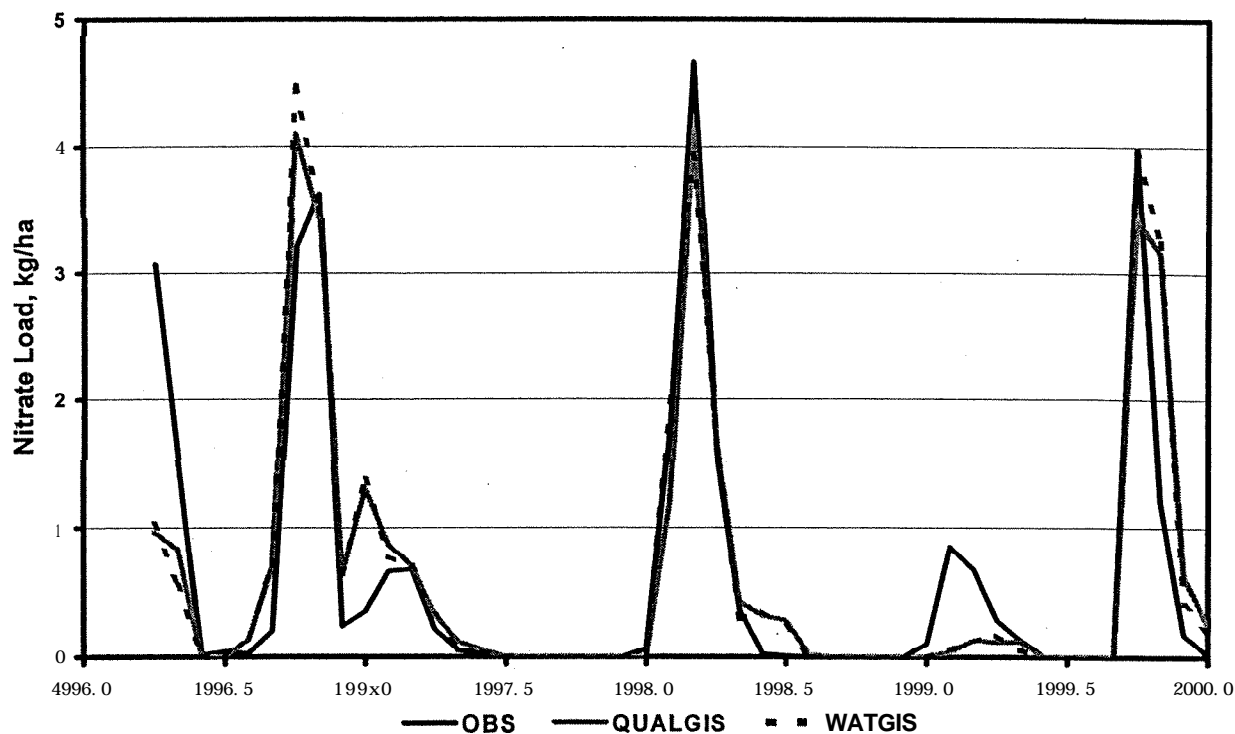


Figure 4. Predicted and observed nitrate-nitrogen load at the outlet of S4 watershed for 1996-99.

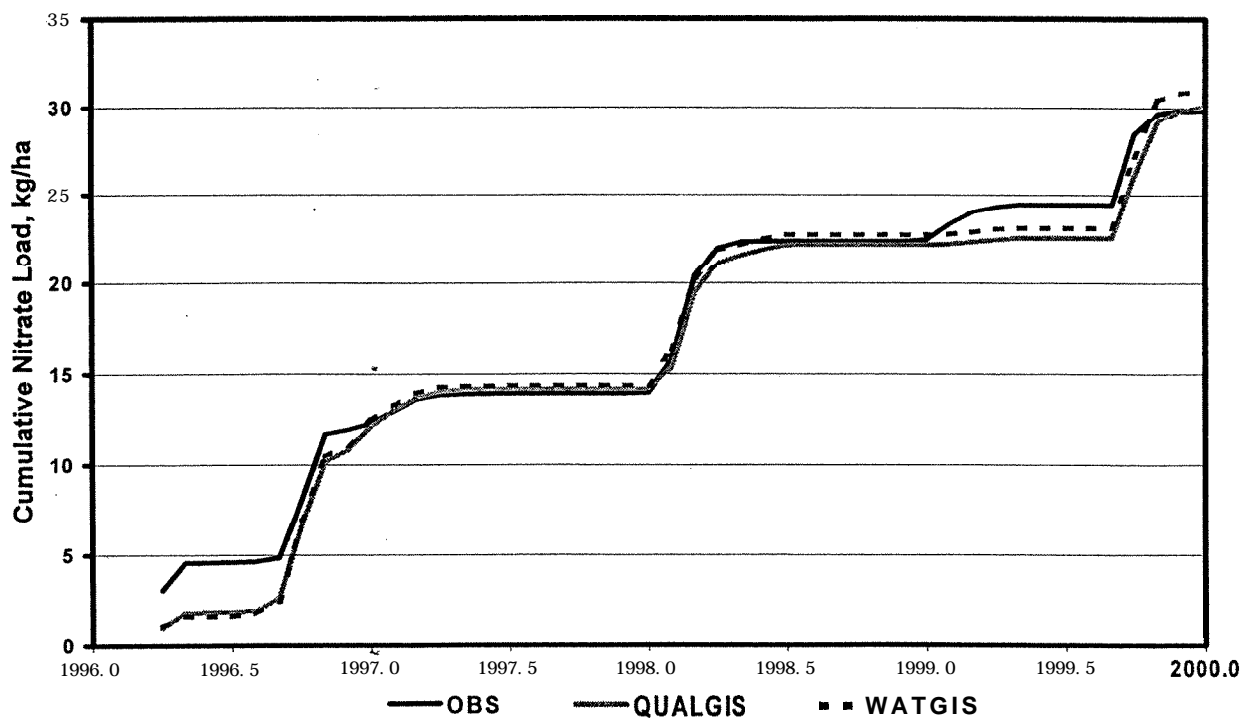


Figure 5. Predicted and observed cumulative nitrate-nitrogen load at the outlet of S4 watershed for 1996-99.

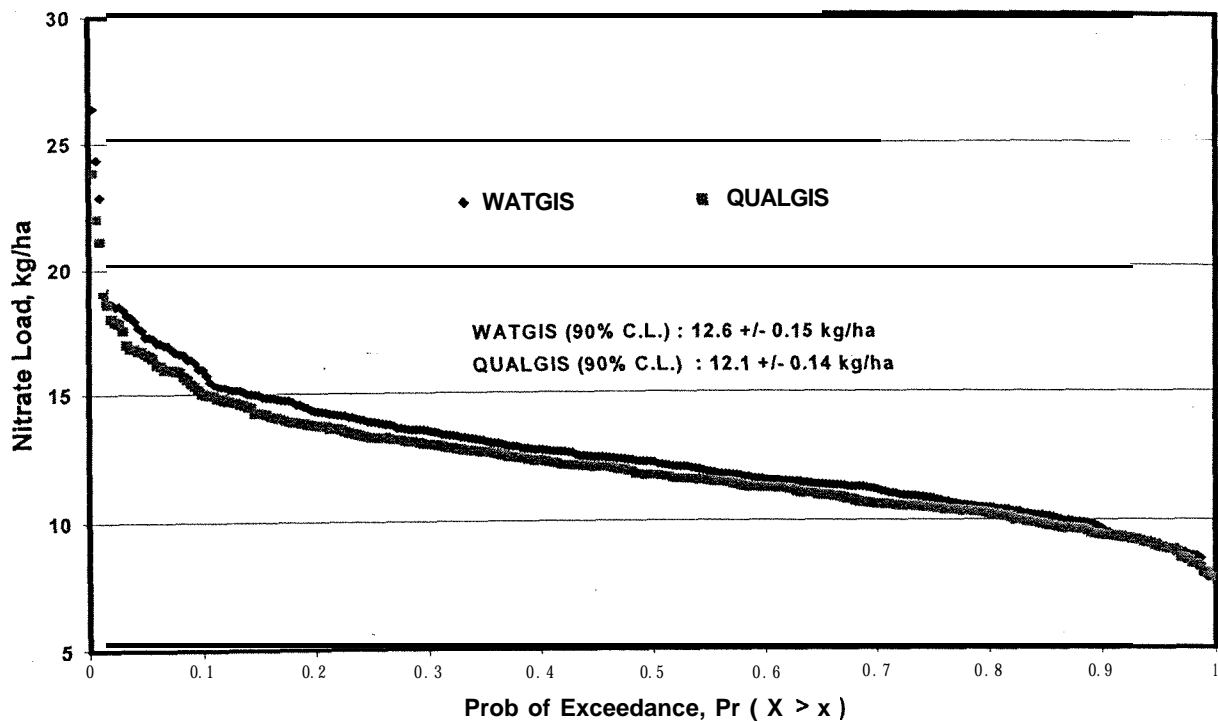


Figure 6. Cumulative distribution of predicted nitrate load as a function of uncertainty in field exports.

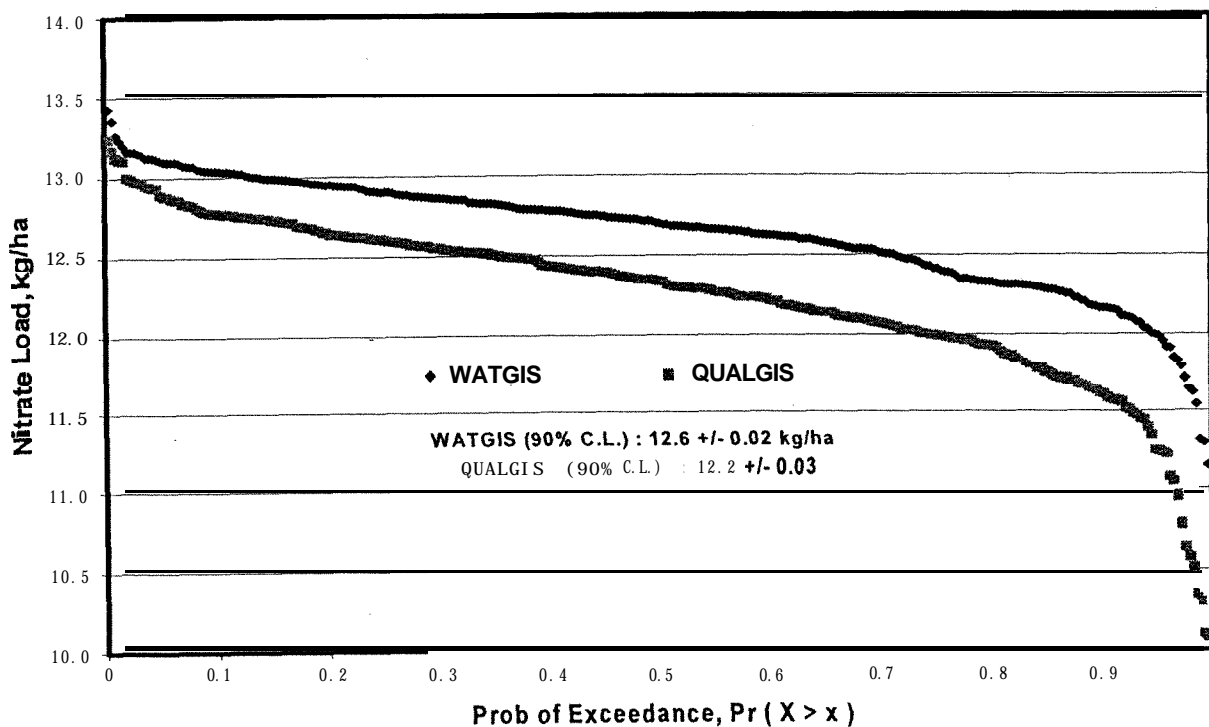


Figure 7. Cumulative distribution of predicted nitrate load as a function of uncertainty in decay coefficient.

Technical Sessions



13 Uncertainty Analysis in Water Quality Modeling (Sponsoring Committee: SW-21)

Moderator: Devendra M Amatya, North Carolina State Univ, Raleigh, NC

Location: Comisky

<u>Paper #</u>	<u>Presentation Title</u>
	Introduction
022006	A Probabilistic Approach to Spray Drift Exposure Assessment to Non-Target Plants/Crops from Herbicide Ground Sprays Tharacad S. Ramanarayanan, Aventis CropScience, Research Triangle Park, NC (TS Ramanarayanan, R Allen, MG Dobbs)
022007	Effect of Model Structure on the Uncertainty of Results from Watershed Scale Water Quality Models Glenn P. Fernandez, North Carolina State Univ, Raleigh, NC (GP Fernandez, GM Chescheir, DM Amatya, RW Skaggs)
022008	Calibration of Hydrologic Models Aida Mendez, Univ of Minnesota, St Paul, MN (A. Mendez, BN Wilson, GR Sands, P Gowda)
022009	Water Quality Management by Using AnnAGNPS Qianhong Tang, Kansas State Univ, Manhattan, KS (Q Tang)
022010	A Data-Mining Approach to Assessing Scale Response in Water Quality Constituent Evolution in Runoff Paul S. Miller, Purdue Univ, West Lafayette, IN (PS Miller, BA Engel, RH Mohtar)
022011	A Probabilistic Approach to Non-Target Plants/Crops Risk Assessment from Herbicide Exposure through Runoff Tharacad S. Ramanarayanan, Aventis CropScience, Research Triangle Park, NC (TS Ramanarayanan, R Allen, MG Dobbs, M Williams, M Cheplick, J Giddings, W Warren-Hicks)
022012	Effect of Spatial Data Resolution on SWAT Output Uncertainty Amy S. Cotter, Univ of Arkansas, Fayetteville, AR (AS Cotter, I Chaubey, TA Costello, MA Nelson, T Soerens)
022013	Incorporating Uncertainty Analysis in SWAT2000 Model Predictions Teymour Sohrabi, Univ of Maryland, College Park, MD (T Sohrabi, A Shirmohammadi, T-W Chu, H Montas)

14 Water Table Management, Nitrate Remediation on Subsurface Drained Landscapes and Drainage Research (Sponsoring Committee: SW-231)

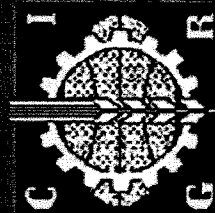
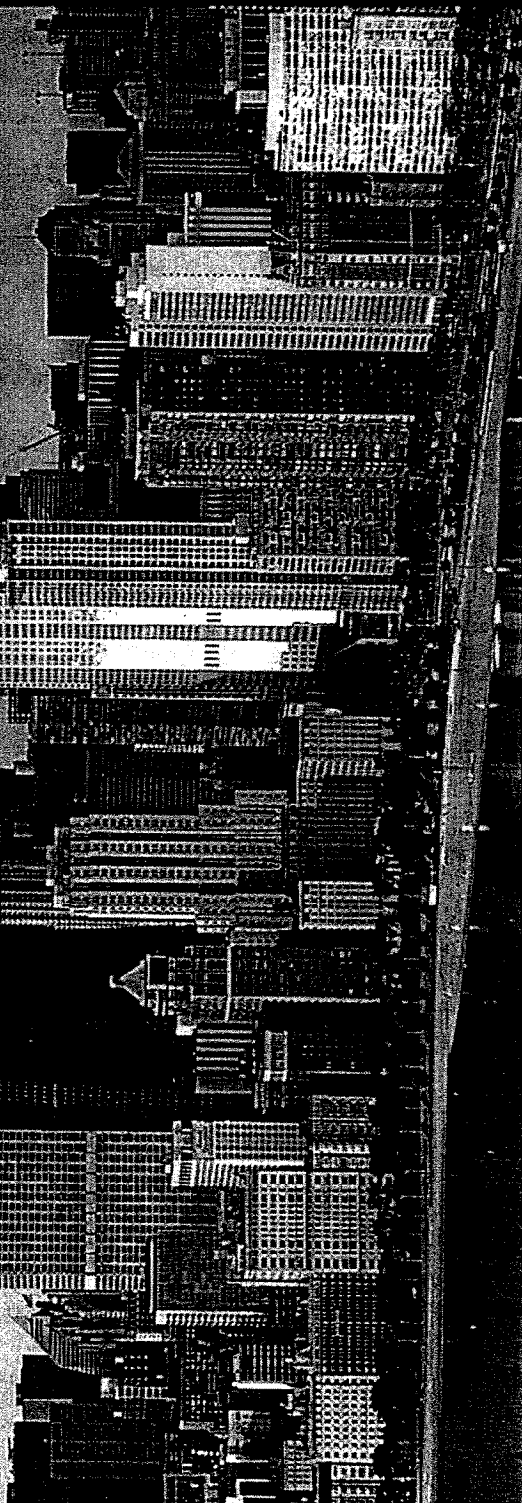
Moderator: Larry C Brown, Ohio State Univ, Columbus, OH

Location: Regency A

<u>Paper</u>	<u>Presentation Title</u>
	Introduction
022014	Analysis to Assess Potential Economic Benefits of Water Table Management by Subirrigation Harold W Belcher, Michigan State Univ, East Lansing, MI (HW Belcher)
022015	Subsurface Drain Modificaitons to Reduce Nitrate Losses in Drainage Dan B Jaynes, USDA-ARS-National Soil Tilth Lab, Ames, IA (DB Jaynes, TC Kaspar, TB Moorman, TB Parkin)

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